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RESULTS OF TESTS ON A 0.111-SCALE SPACE SHUTTLE VEHICLE SIMULATED ELEVON/WING GAP HEAT TRANSFER MODEL (53-0) IN THE AMES RESEARCH CENTER 3.5-FOOT HYPERSONIC WIND TUNNEL (OH15)

by

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Prepared under NASA Contract Number NAS9-13247

by

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for

Engineering Analysis Division

Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

WIND TUNNEL TEST SPECIFICS:

Test Number:	ARC 3.5 Ft. HWT-173
NASA Series Number:	OH15
Model Number	53-0
Test Dates:	Sept. 12 - 20, 1973
Occupancy Hours:	72

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ABSTRACT

Aerodynamic heating in gaps is an area of major concern on the Space Shuttle Orbiter since it is not amenable to treatment solely by analysis. Model 53-0 was tested to evaluate the effect of elevon deflection, gap geometry, and boundary layer state on elevon/wing gap heating. Testing was conducted in the Ames Research Center 3.5-foot Hypersonic Wind Tunnel at a nominal Mach number of 5.1 and the model at zero angles of attack, yaw, and roll.

The primary source of information for this report is reference 2.

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INDEX OF MODEL FIGURES

NOMENCLATURE

Symbol	Computer Symbol	Description
b		thickness of model skin
C		specific heat of model skin material, BTU/lb mass
C_0, C_1, C_2		constants in curve fit for C over model wall temperature range
c_p		specific heat at constant pressure of air stream (perfect gas value), BTU/lb
CHAN	CHAN	recording-system channel
H_{aw}	HAW	adiabatic wall enthalpy, BTU/lb mass or joule/kilogram
H_t	HT	free-stream total enthalpy, BTU/lb mass or joule/kilogram
H_{w_i}	HW	enthalpy based on model wall temperature for given T/C location at initial time, BTU/lb mass or joule/kilogram
h	H	heat-transfer coefficient at model wall for given T/C location
h_s	HS	stagnation-point heat-transfer coefficient for reference sphere
h/h_s(X.XXX)	H/HS(X.XXX)	ratio of model heat-transfer coefficient to heat-transfer coefficient of reference sphere for H_{aw}/H_t= X.XXX (1.0, 0.9, 0.85)
L	LENGTH	model reference length, inches
M_∞	MACH	free-stream Mach number
P_t	PT	free-stream total pressure, PSI or atmospheres
$\dot{q}_i$	Q	heat-transfer rate at model wall for given T/C location at initial time, BTU/ft^2 sec
$\dot{q}_s$	QS	stagnation-point heat-transfer rate for reference sphere at initial time

NOMENCLATURE (Continued)

Symbol	Computer Symbol	Description
R_s	RS	reference sphere radius at model scale equivalent to 0.305 m (1 ft) for full-scale vehicle
Re_∞/ft	RE/FT	free-stream Reynolds number per foot; also, per meter
$Re_{\infty,L}$	REL	free-stream Reynolds number based on model reference length, L
St(X.XXX)	ST(X.XXX)	Stanton number based on free-stream flow conditions and the model heat-transfer coefficient for H_{aw}/H_t= X.XXX (1.0, 0.9, 0.85)
T		temperature, degrees Rankine/Fahrenheit
T_t	TT	free-stream total temperature, degrees Rankine/ Fahrenheit
T_{w_i}	TW	model wall temperature for given T/C location at initial time, degrees Rankine/Fahrenheit
T/C	T/C	thermocouple
t	T	time, sec.
t_i	TIME	initial time (before model insertion into flow) extrapolated from $f(T_w)$ vs time, sec.
V	V	velocity, ft/sec
W		density of model skin material, lb mass/ft^3
μ	MU	viscosity of air, $\frac{lb - sec}{ft^2}$
ρ	RHO	density of air, slugs/ft = $\frac{lb - sec^2}{ft^4}$

Subscripts

aw		adiabatic wall
i		initial value before model insertion into tunnel flow

NOMENCLATURE (Concluded)

Subscripts

PG	perfect gas (calorically and thermally perfect gas)
s	reference sphere
t	free-stream total condition
w	wall
∞	free-stream
1	conditions upstream of shock
2	conditions downstream of shock

Symbol	Computer Symbol	Description
T'_{aw}		perfect gas adiabatic wall temperature
C'_{aw}		specific heat calculated at T'_{aw}

CONFIGURATIONS INVESTIGATED

The model consists of a scale representation of the wing/elevon gap geometry inserted in the existing basic model 15-0 flat plate carrier. This stainless steel flat plate carrier is 2 inches thick, 27 inches wide, and 60 inches long with a wedge leading edge. The carrier is designed to accept 24-inch wide inserts with lengths of 6 or 12 inches. This carrier can be seen in Figure 1, which shows the elevon installed at a station 24 inches aft of the carrier leading edge. The elevon can be shifted in the carrier all the way aft to station 48. Flat plate inserts are installed forward and aft of the elevon. This model has been designated as model 53-0.

The use of existing instrumented flat plate inserts forward of the elevon permitted heating rates to be established upstream of the elevon. Thermocouples were used on thin skin areas of the elevon to establish heating. All instrumentation leads were routed under the flat plate inserts to the aft end of the carrier and then down into the sting.

The elevon/wing gap model details are shown in Figures 1a and 1b, which are drawings of the elevon assembly. Test details and a full set of model drawings are contained in the Pretest Report (Ref. 1). The elevon is a 0.111-scale representation of the Space Shuttle Orbiter elevon/wing gap hinge line geometry at the mid-span position of the elevon. The insert is a split elevon with all instrumentation in the right hand elevon.

The elevon is basically made up of 3 major assemblies: cove, base plate, and deflectable flap. The flap is mechanically attached to a hinge rod, which is part of the base plate. A continuous hinge rod spacer prevents air flow entering the elevon/wing gap from flowing around the hinge and out under the flap. Flow stoppers prevent spanwise flow in the elevon/wing gap. Brackets are installed under the flap to obtain elevon deflections from 0° to 25° in 5° increments. Different deflections can be obtained on the two flaps to permit the evaluation of differential deflections.

Several cove assemblies were provided to permit the effect of cove entrance radius and elevon/wing gap width to be evaluated. In addition, provision was made to offset the elevon surface below that of the cove to evaluate elevon surface misalignment.

Another capability included in the model was to evaluate the effect of elevon seal leakage on elevon/wing gap heating. This was accomplished by removing the hinge rod spacer (located between the hinge rod and the bottom of the elevon) and providing replacements with spanwise slots of different heights. With one of these slotted spacers installed, a leak of known area permits flow entering the elevon/wing gap to pass over the hinge rod and exit under the elevon.

INSTRUMENTATION

The model is constructed of 17-4 PH stainless steel. Thin skin inserts made of 17-7 PH stainless steel were used on the cove and flap for instrumented areas. For this test series, the model was instrumented with a total of 70 chromel-constantan thermocouples spot-welded to the skin. These thermocouples were located in two parallel rows on either side of the model ℄ on the elevon and cove. Thermocouples (T/C's) 101 thru 150 were located on the elevon and T/C's 151-170 were located on the cove.

Existing instrumented flat plate inserts (from model 15-0) were used forward of the elevon assembly. These inserts were fabricated of 17-4 PH stainless steel and had a single row of thermocouples along the model ℄. With the elevon at station 24, a total of 8 additional T/C's were available on the flat plate inserts (T/C's 1-5, 16, 18 and 19). When the elevon is located at station 48, a total of 18 additional T/C's were available on the flat plate inserts (T/C's 1 - 15, 16, 18 and 19).

To aid in evaluating the heat transfer data, static pressure measurements were made at several locations on the model. Statham Absolute Transducers (PA 208) available at NASA/Ames were used. The transducers were mounted on the model to keep the line from the orifice as short as possible. Two measurements were made on the flap surface, two in the plenum at the bottom of the elevon/wing gap, and two on the underside of the flap.

A complete tabulation of station, depth, spanwise location and local skin thickness for all thermocouples is given in Table III. In addition, the wetted length from the tangency point is given for each T/C on the elevon.

TEST FACILITY DESCRIPTION

The NASA-Ames 3.5-Foot Hypersonic Wind Tunnel is a closed-circuit, blowdown-type tunnel capable of operating at nominal Mach numbers of 5, 7, and 10 at pressures to 1800 psia and temperatures to 3400°R for run times to four minutes. The major components of the facility include a gas storage system where the test gas is stored at 3000 psi, a storage heater filled with aluminum-oxide pebbles capable of heating the test gas to 3400°R, axisymmetric contoured nozzles with exit diameters of 42 inches for generating the desired Mach number, and a 900,000 ft^3 vacuum storage system which operates to pressures of 0.3 psia. The test section itself is an open-jet type enclosed within a chamber approximately 12 feet in diameter and 40 feet in length, arranged transversally to the flow direction.

A model support system is provided that can pitch models through an angle of attack range of -20 to +20 degrees, in a vertical plane, about a fixed point of rotation on the tunnel centerline. This rotation point is adjustable from 1 to 5 feet from the nozzle exit plane. The model normally is out of the test stream (strut centerline 37 inches from tunnel centerline) until the tunnel test conditions are established, after which it is inserted. Insertion time is adjustable to as little as 1/2 second, and models may be inserted at any strut angle.

A high-speed, analog-to-digital data acquisition system is used to record test data on magnetic tape. The present system is equipped to measure and record the outputs from 80 transducers in addition to 20 channels of tunnel parameters.

DATA REDUCTION*

All test data were reduced at the NASA/Ames Research Center using the data reduction techniques outlined below. The thermocouple data were reduced using the one-dimensional, thin-wall equation:

$$\dot{q} = WCb \frac{dT_w}{dt} = h \left(H_{aw} - H_w\right) \equiv hH_t \left(\frac{H_{aw}}{H_t} - \frac{H_w}{H_t}\right) \tag{1}$$

which neglects heat-conduction losses.

Assuming that W and h are constant and

$$C = C_o + C_1 T_w + C_2 T_w^2 \text{ for } T_w \text{ ranges,} \tag{2}$$

the integration of equation (1) for $t = t_i$ to t and $T_w = T_{w_i}$ to T_w yields the linear equation:

$$f(T_w) = -\ln\left(\frac{T'_{aw} - T_w}{T'_{aw} - T_{w_i}}\right) - \left[\frac{C_1}{C'_{aw}} + \frac{C_2}{C'_{aw}}\left(T'_{aw} + \frac{T_w + T_{w_i}}{2}\right)\right](T_w - T_{w_i})$$

$$= \frac{hc_p}{WC'_{aw}\,b}\ (t - t_i) \tag{3}$$

where it is defined that:

$$T'_{aw} \equiv \frac{H_{aw}}{c_p} \equiv \frac{H_{aw}}{H_t}\ \frac{H_t}{c_p} \geq (T_{aw})_{PG} \tag{4}$$

$$C'_{aw} \equiv C_o + C_1 T'_{aw} + C_2 T'^{\,2}_{aw} \tag{5}$$

$\neq$ specific heat at adiabatic wall temperature

The form of Eq (3) is $f(T_w) = mt + a$ where m is the slope and a is the intercept for a straight line if heat-conduction errors are negligible. Thus, deviations from a straight line can indicate heat-conduction effects.

* Data Reduction Section provided by W. K. Lockman, ARC.

The slope, m, of $f(T_w)$ vs. t from Eq (3) is computed by a least-squares, straight-line fit over a finite time interval (approx. 1 sec.) beginning when the model reaches uniform tunnel flow. The value of the heat-transfer coefficient, h, is then determined from:

$$h = \frac{WC'_{aw}b}{c_p} m \tag{6}$$

Using this value of h, the heat-transfer rate is evaluated at the initial time, t_i, when the model is isothermal at the initial wall enthalpy, H_{w_i}

$$\dot{q} = \dot{q}_i = h \left(H_{aw} - H_{w_i}\right) \equiv hH_t \left(\frac{H_{aw}}{H_t} - \frac{H_{w_i}}{H_t}\right) \tag{7}$$

where H_{aw}/H_t is the same value used to evaluate h. The resultant value of $\dot{q}$ is independent of the value of H_{aw}/H_t used for both the h and q evaluations.

The reference sphere heating is also evaluated at the initial wall enthalpy by the method of Fay and Riddell (ref. 3):

$$\dot{q}_s = h_s \left(H_t - H_{w_i}\right) \equiv h_s H_t \left(1.0 - \frac{H_{w_i}}{H_t}\right) \tag{8}$$

The model-to-sphere ratio of heat-transfer coefficients is then determined from Eqs. (7) and (8) as

$$\frac{h}{h_s} = \frac{\dot{q}_i}{\dot{q}_s} \left[\frac{1.0 - H_{w_i}/H_t}{H_{aw}/H_t - H_{w_i}/H_t}\right] \tag{9}$$

where $\dot{q}_i$ is constant for all values of H_{aw}/H_t.

To determine h/h_s for various values of H_{aw}/H_t, the particular value of H_{aw}/H_t is substituted into Eq. (9).

The Stanton number is defined as

$$St \equiv \frac{h}{\rho u} = \frac{q_i}{\rho u(H_{aw} - H_{w_i})} \tag{10}$$

where for free-stream conditions, $\rho u = \rho_\infty V_\infty$.

The calculations of the model heating, reference sphere heating, and Reynolds number included the corrections of NACA report 1135 (ref. 4) for calorically imperfect, thermally perfect air. Keyes' equation for viscosity (see ref. 5) was also used for the sphere heating and Reynolds number computations:

$$\mu = \frac{0.0232 \times 10^{-6}\ T^{0.5}}{1 + \frac{220}{T} \quad 10^{-9/T}} \tag{11}$$

where the units for T and μ are °R and lb-sec/ft^2, respectively.

Test data are available through the following:

W. K. Lockman
NASA-Ames Research Center
Mail Stop 229-1
Moffett Field, California 94035

Phone: (415) 965-6211

REFERENCES

1. SD73-SH-0269, "Pretest Information For A Simulated 0.111-Scale SSV Elevon/Wing Gap Heat Transfer Model (53-0) in the Ames Research Center 3.5-Foot Hypersonic Wind Tunnel, Test OH15", By C. L. Berthold, September 6, 1973.

2. Grumman Aerospace Corporation Thermodynamics Report TPM-001-33, "Final Report Analysis and Evaluation-Elevon/Wing and Elevon/Elevon Gap Heating Wind Tunnel Tests (Model 53-0)", By R. Bullis, L. Hemmerdinger and W. Timlen, March 1974.

3. Fay, J. A.; and Riddell, F. R.: Theory of Stagnation Point Heat Transfer in Dissociated Air. J. Aeron, Sci.; Vol. 25, No. 1, Feb. 1958, pp. 73-85.

4. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rept. 1135, 1953.

5. Bertram, Mitchel H.: Comment on "Viscosity of Air." J. Spacecraft Rockets, Vol. 4, No. 2, Feb. 1967, pp. 287-288.

TABLE I.

TEST : OH15

DATE :

NOMINAL
TEST CONDITIONS

MACH NUMBER	REYNOLDS NUMBER (per foot)	DYNAMIC PRESSURE (pounds/sq. inch)	STAGNATION TEMPERATURE (degrees Rankine)
5.1	0.74×10^6	3.372	2460
5.1	1.48×10^6	6.743	2460

BALANCE UTILIZED: __________

	CAPACITY:	ACCURACY:	COEFFICIENT TOLERANCE:
NF			
SF			
AF			
PM			
RM			
YM			

COMMENTS:

TABLE II.

ELEVON/WING TEST CONDITIONS

Run	Elevon Station	Elevon Deflection	Cove Gap	Cove Radius	Tunnel P_t	Tunnel T_t	R_E/F_T x 10^{-6}	Remarks
	In.	Degrees	In.	In.	PSIA	^oR		
1	36	0	.056	.056	96.6	2000	.65	
1000	36	0	.056	.056	118.8	2010	.79	
2	24	0	.056	.056	80.5	1908	.59	
3	24	5	.056	.056	80.9	1938	.57	
4	24	10	.056	.056	92.4	2056	.59	
5	24	15	.056	.056	98.1	2017	.65	
7	24	0	.056	.028	94.5	1973	.65	
8	24	10	.056	.028	101.1	1907	.74	
9	24	15	.056	.028	102.6	2022	.68	
10	24	0	.028	.056	110.2	2063	.71	
11	24	10	.028	.056	110.6	1987	.75	
12	24	15	.028	.056	110.4	2067	.70	
13	24	0	.083	.056	110.5	1964	.77	
14	24	10	.083	.056	110.4	2047	.71	
15	24	15	.083	.056	111.0	1929	.79	
16	24	10	.056	.056	109.0	2102	.67	Seal Leakage(.014")*
17	24	15	.056	.056	107.7	1962	.75	Seal Leakage(.014")
18	24	10	.056	.056	110.0	2085	.69	Seal Leakage(.042")
19	24	15	.056	.056	111.0	1947	.79	Seal Leakage(.042")
20	24	10	.056	.056	104.0	1983	.71	Seal Leakage(.056")
21	24	15	.056	.056	105.4	1996	.71	Seal Leakage(.056")
22	48	0	.056	.056	258.8	2054	1.66	
23	48	5	.056	.056	295.7	2090	1.85	
24	48	10	.056	.056	293.2	2012	1.95	
26	48	10	.056	.028	283.6	2001	1.91	
27	48	0	.028	.056	290.2	1968	2.01	
28	48	10	.028	.056	296.3	2076	1.87	
30	48	10	.083	.056	295.0	1884	2.19	
31	48	5	.056	.056	296.0	2083	1.86	Seal Leakage(.014")
32	48	10	.056	.056	284.4	2037	1.86	Seal Leakage(.014")
33	48	10	.056	.056	277.2	2031	1.82	Seal Leakage(.042")
34	48	10	.056	.056	290.4	1987	1.98	Seal Leakage(.056")

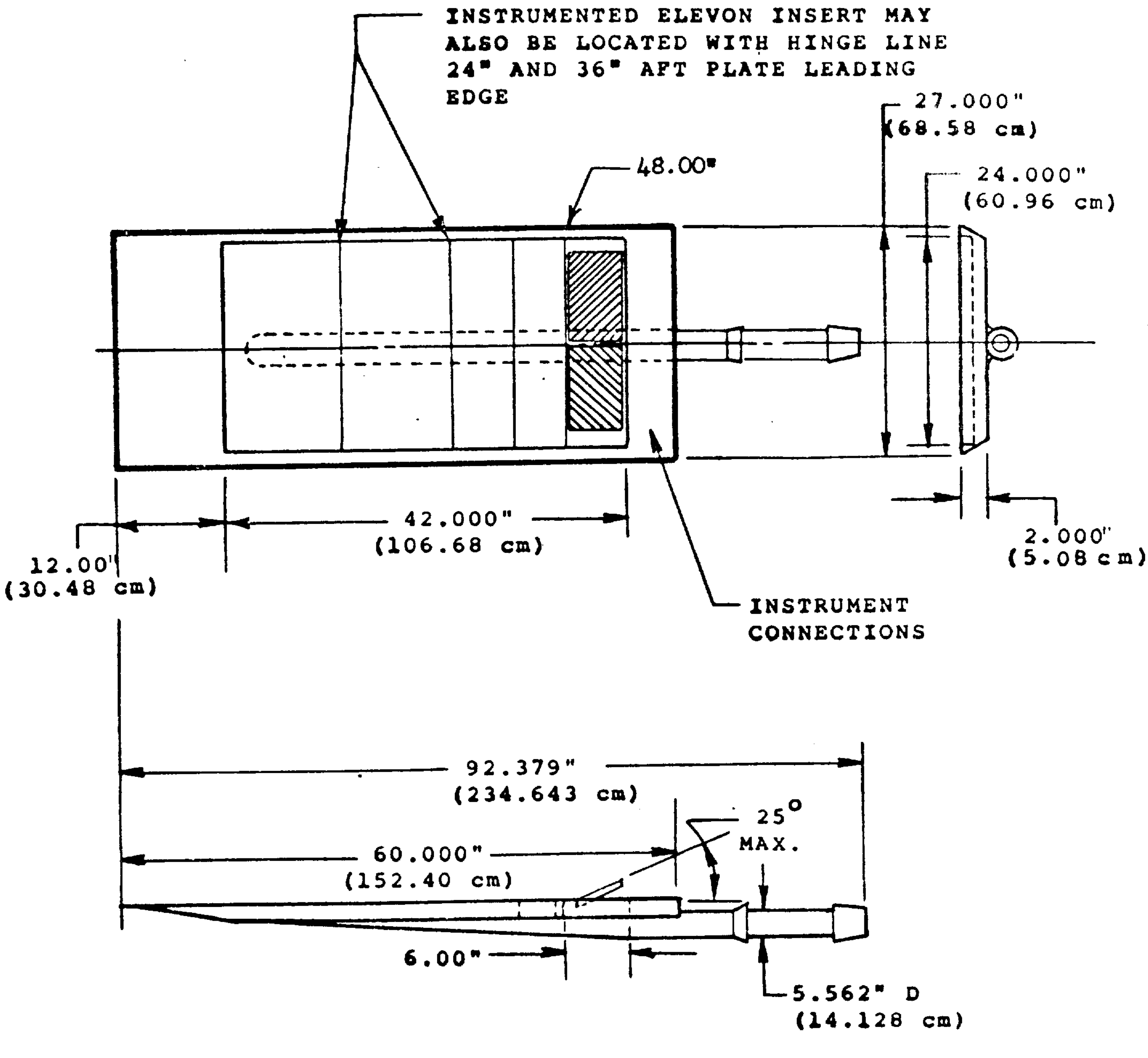
* ( ) Indicates Height of Leakage Area

TABLE III. - ELEVON/WING GAP MODEL THERMOCOUPLE LOCATIONS

Thermocouple No.	Station		Depth	Spanwise Location	Skin Thickness	Wetted Length
	Inches from Carrier L.E.		Inches from Carrier Top	Inches from Carrier ℄ (Right +/Left -)	Inches	Inches from Tangency Pt. (Forward - Aft +)
	@ STA 24	@ STA 48				
101	24.03	48.03	.555	-.493	.0081	-.854
102	24.11	48.11	.385	-.493	.0077	-.678
103	24.22	48.22	.175	-.493	.0077	-.550
104	24.26	48.26	.115	-.493	.0072	-.489
105	24.31	48.31	.085	-.493	.0150	-.428
106	24.36	48.36	.070	-.493	.0152	-.364
107	24.41	48.41	.040	-.493	.0160	-.305
108	24.47	48.47	.020	-.493	.0159	-.244
109	24.52	48.52	.015	-.493	.0160	-.183
110	24.58	48.58	.010	-.493	.0160	-.122
111	24.64	48.64	.003	-.493	.0158	-.061
112	24.7	48.7	0	-.493	.0157	0
113	24.8	48.8	0	-.493	.0160	+.1
114	24.9	48.9	0	-.493	.0163	.2
115	25.1	49.1	0	-.493	.0162	.4
116	25.4	49.4	0	-.493	.0160	.7
117	25.7	49.7	0	-.493	.0158	1.0
118	26.1	50.1	0	-.493	.0160	1.4
119	26.6	50.6	0	-.493	.0157	1.9
120	27.1	51.1	0	-.493	.0153	2.4
121	27.6	51.6	0	-.493	.0153	2.9
122	28.1	52.1	0	-.493	.0155	3.4
123	28.6	52.6	0	-.493	.0154	3.9
124	29.1	53.1	0	-.493	.0152	4.4
125	29.6	53.6	0	-.493	.0152	4.9
126	24.03	48.03	.555	.493	.0080	-.854
127	24.11	48.11	.385	.493	.0075	-.678
128	24.22	48.22	.175	.493	.0072	-.550
129	24.26	48.26	.115	.493	.0072	-.489
130	24.31	48.31	.085	.493	.0150	-.428
131	24.36	48.36	.070	.493	.0160	-.364
132	24.41	48.41	.040	.493	.0161	-.305
133	24.47	48.47	.020	.493	.0164	-.244
134	24.52	48.52	.015	.493	.0162	-.183
135	24.58	48.58	.010	.493	.0161	-.122
136	24.64	48.64	.003	.493	.0160	-.061
137	24.7	48.7	0	.493	.0161	0
138	24.8	48.8	0	.493	.0160	+.1
139	24.9	48.9	0	.493	.0161	.2
140	25.1	49.1	0	.493	.0162	.4
141	25.4	49.4	0	.493	.0157	.7
142	25.7	49.7	0	.493	.0154	1.0
143	26.1	50.1	0	.493	.0153	1.4
144	26.6	50.6	0	.493	.0153	1.9
145	27.1	51.1	0	.493	.0162	2.4
146	27.6	51.6	0	.493	.0152	2.9
147	28.1	52.1	0	.493	.0161	3.4

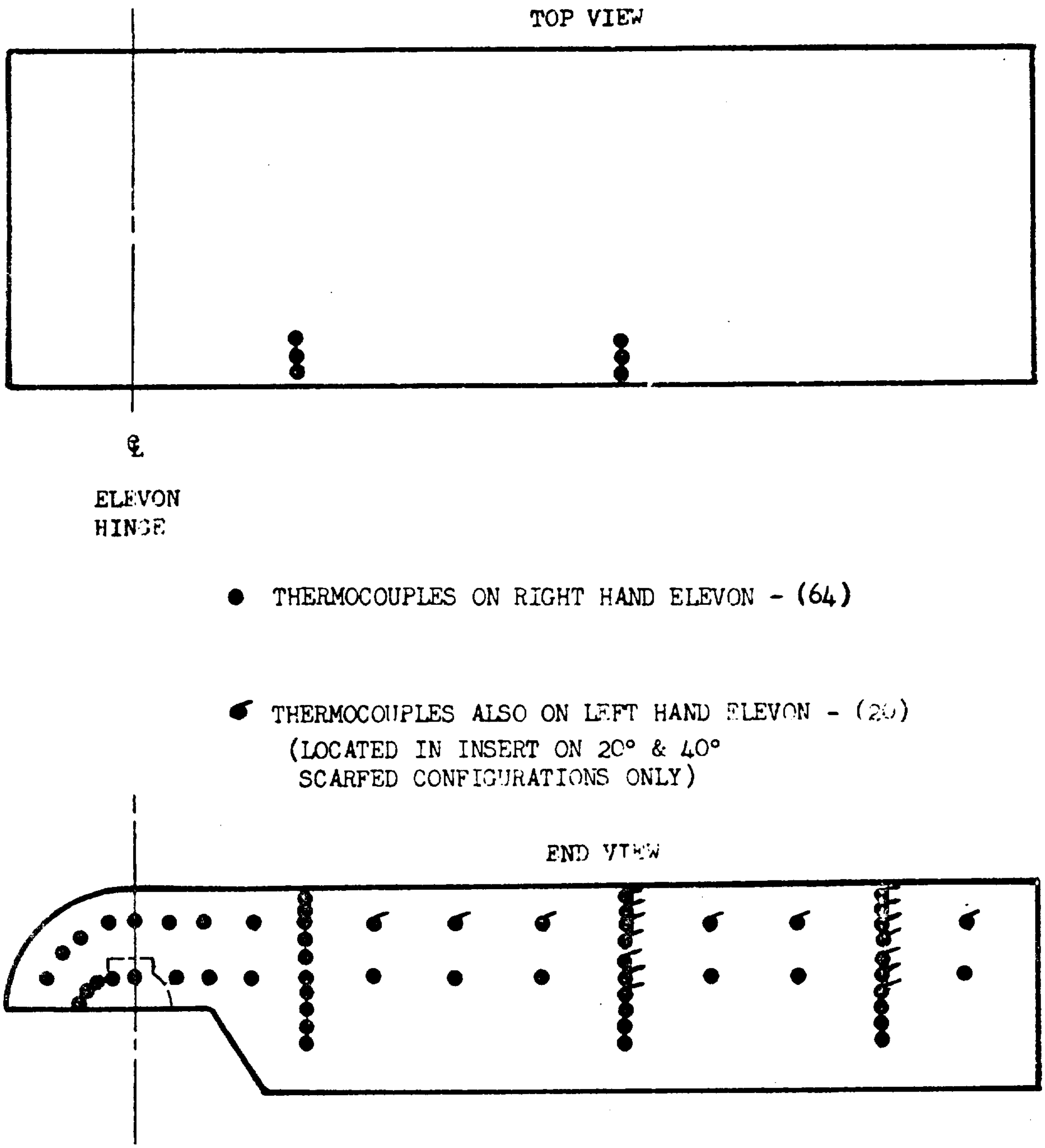
TABLE III. - ELEVON/WING GAP MODEL THERMOCOUPLE LOCATIONS
(Concluded)

Thermocouple No.	Station		Depth	Spanwise Location	Skin Thickness	Wetted Length
	Inches from Carrier L.E.		Inches from Carrier Top	Inches from Carrier ℄ (Right +/Left -)	Inches	Inches from Tangency Pt. (Forward - Aft +)
	@ STA 24	@ STA 48				
148	28.6	52.6	0	.493	.0152	3.9
149	29.1	53.1	0	.493	.0152	4.4
150	29.6	53.6	0	.493	.0160	4.9
151	23.07	47.09	0	-.50	.0150	
152	23.93	47.93	0	-.50	.0140	
153	24.12	48.12	0	-.50	.0140	
154	24.32	48.32	0	-.50	.0140	
155	24.40	48.40	.056	-.50	.0140	
156	24.32	48.32	.112	-.50	.0140	
157	24.16	48.16	.155	-.50	.0060	
158	24.04	48.04	.310	-.50	.0060	
159	23.95	47.95	.510	-.50	.0060	
160	23.94	47.94	.940	-.50	.0060	
161	23.07	47.09	0	.515	.0150	
162	23.93	47.93	0	.515	.0140	
163	24.12	48.12	0	.515	.0140	
164	24.32	48.32	0	.515	.0140	
165	24.40	48.40	.056	.515	.0140	
166	24.32	48.32	.112	.515	.0140	
167	24.16	48.16	.155	.515	.0060	
168	24.04	48.04	.310	.515	.0060	
169	23.95	47.95	.510	.515	.0060	
170	23.94	47.94	.940	.515	.0060	
1	12.55	24.55	0	0	.0158	
2	13.5	25.5	0	0	.0151	
3	15.505	27.505	0	0	.0150	
4	16.5	28.5	0	0	.0151	
5	17.45	29.45	0	0	.0156	
6	-	30.55	0	0	.0149	
7	-	31.5	0	0	.0127	
8	-	33.505	0	0	.0133	
9	-	34.5	0	0	.0153	
10	-	35.45	0	0	.0160	
11	-	36.55	0	0	.0132	
12	-	37.5	0	0	.0130	
13	-	39.505	0	0	.0109	
14	-	40.5	0	0	.0125	
15	-	41.45	0	0	.0138	
16	18.55	42.55	0	0	.0137	
18	21.27	45.27	0	0	.0138	
19	22.19	46.19	0	0	.0142	



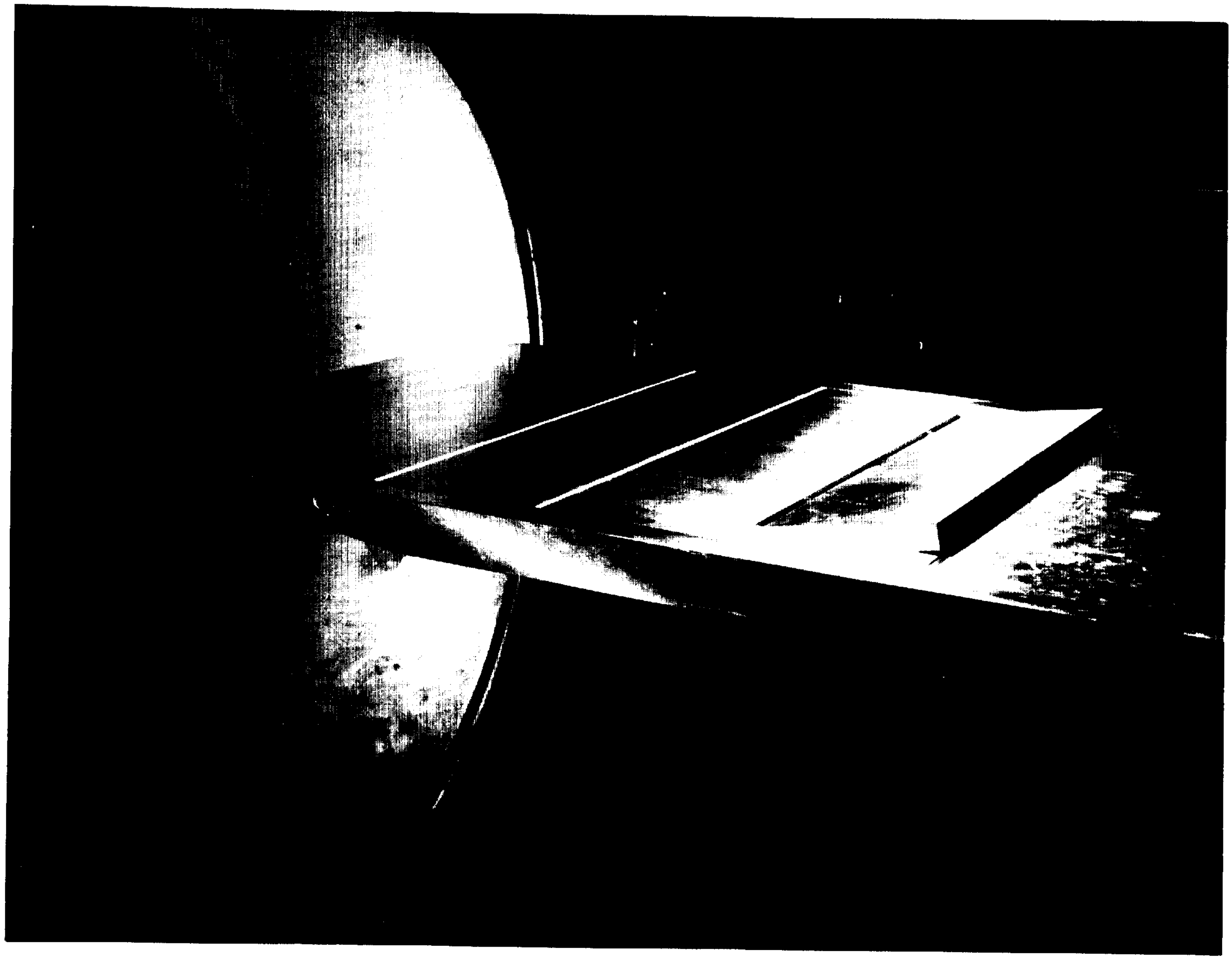
a. Carrier Plate

Figure 1. - Model Figures



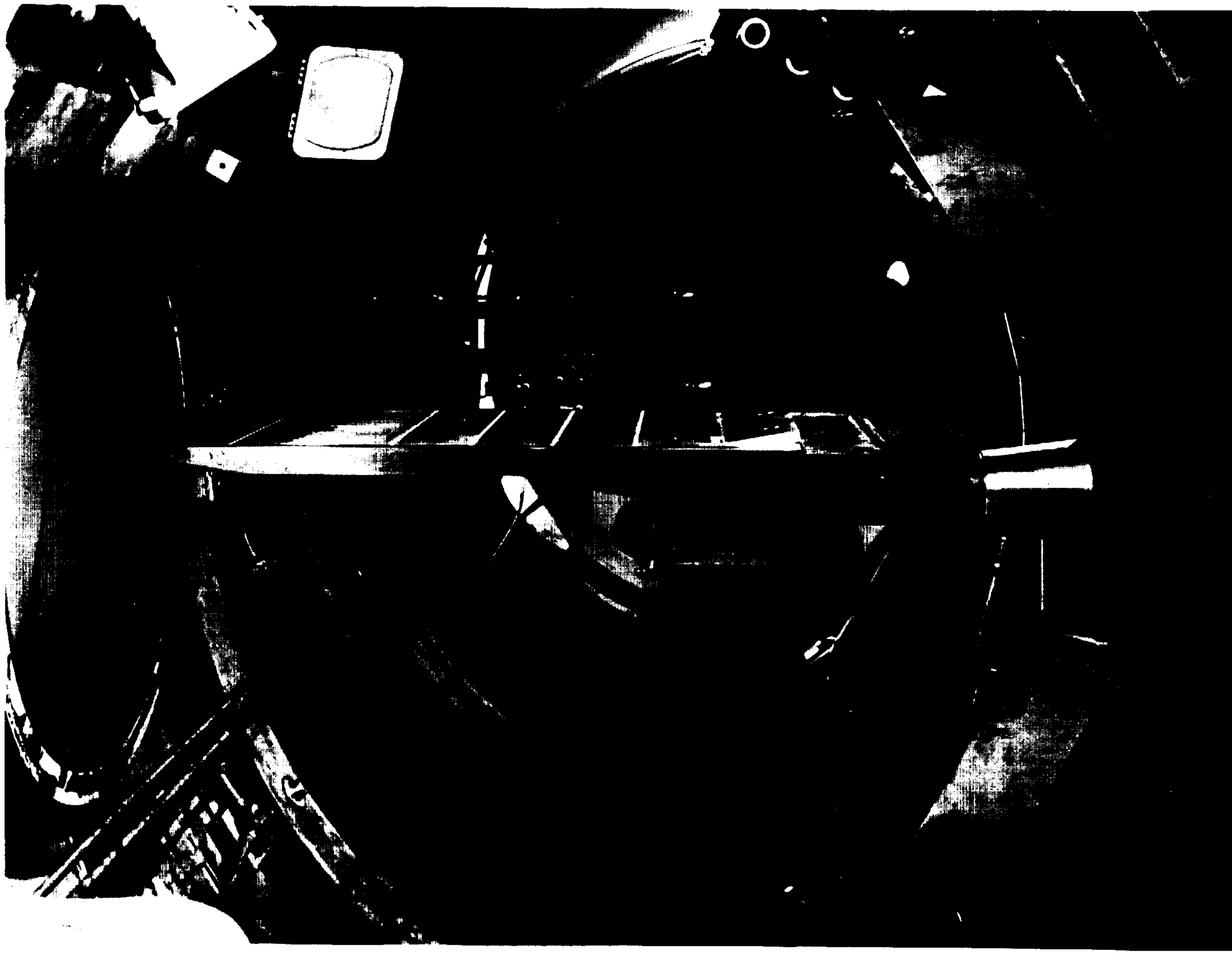
b. Instrumented Elevon

Figure 1. - Concluded.



a. Model Installed in Tunnel With Elevon at Station 24

Figure 2. - Model Photographs.



b. Model Installed in Tunnel With Elevon at Station 48

Figure 2. - Concluded.